TNO Report

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TNO report

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Review of published safety thresholds for human divers exposed to underwater sound

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Veilige maximale geluidsniveaus voor duikers - beoordeling van publicaties

Probleemstelling

Blootstelling aan een hoge intensiteit van onderwatergeluid kan schadelijk zijn voor duikers. Ten gevolge van een dergelijke blootstelling kan gehoorschade ontstaan of, direct als gevolg van het geluid of als gevolg van een paniekreactie, schade aan andere organen. Het is derhalve van belang te weten wat het maximale geluidniveau is dat nog veilig is voor duikers.

Beschrijving van de werkzaamheden

In een eerder uitgevoerd intern TNO kennisinvesteringsproject is een overzicht opgesteld van eerder gepubliceerde geluidniveaus die nog toelaatbaar zijn. In het onderhavige rapport worden de resultaten hiervan gebundeld en overzichtelijk weergegeven, zodat ze voor een breder publiek toegankelijk worden gemaakt. De resultaten worden weergegeven in zogenaamde 'safety thresholds' voor onderwatergeluid voor duikers, in het frequentiebereid van 125 hertz tot 250 kilohertz. Tevens is bekeken waar de diverse publicaties niet met elkaar overeenkomen en is er onderzocht welke publicatie de meest betrouwbare informatie geeft.

Resultaten en conclusies

Er blijken grote verschillen te zijn in de diverse publicaties met betrekking tot maximaal toelaatbare geluidniveaus onderwater voor duikers. De meest betrouwbare geluidniveaus van de diverse publicaties zijn in een tabel weergegeven.

Toepasbaarheid

De weergegeven maximale geluidniveaus zijn relevant voor situaties waar professionele duikers onderwater blootgesteld worden aan onderwatergeluid. Voor recreatieve duikers, die doorgaans minder goed uitgerust zijn qua uitrusting, zijn de risico's groter en moeten de 'safety thresholds' vermoedelijk voorzichtiger gehanteerd worden. De weergegeven niveaus zijn primair bedoeld voor gebruik in relatie tot militaire sonars, maar zijn ook te gebruiken in vergelijkbare situaties met vergelijkbare sonarbronnen bij oceanografisch onderzoek. De weergegeven niveaus zijn niet geschikt om te gebruiken in situaties waar korte geluidimpulsen voorkomen, zoals bij het gebruik van explosieven, heiwerkzaamheden en zogenaamde air-guns.

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Contents

1 Introduction

Divers exposed to high levels of underwater sound can suffer from dizziness, hearing damage or other injuries to other sensitive organs, depending on the frequency and intensity of the sound. Even if not the direct cause, a loud sound may cause injury indirectly by startling an unalerted diver, provoking a potentially threatening panic reaction. For these reasons a number of experimental studies have been undertaken, mainly in the UK and US, into maximum safe sound pressure level as a function of frequency.

This note is a spin-off from a self-funded research project at TNO in which the detection of divers was studied [1]. First, thresholds of human hearing in water (underwater audiograms) are summarised in Section 2. In Section 3, the results of high level exposure studies are reviewed, in the context of possible exposure to sonar transmissions. Discussion and recommendations follow in Section 4.

2 Hearing thresholds

Published measurements of human audiograms in water are surprisingly scarce, and the author is aware of just two: one is published by Gerstein [2] in *American Scientist* (Figure 1 below); the other in UDT conference proceedings by Parvin *et al.* [3] (Figure 2). In both figures, the audiograms are in the form of a sound pressure level threshold with a reference pressure of one micropascal (1 μPa), for both air and water[1] (see also section 4.1). Further, no correction is applied for the difference in impedance between air and water. Thus, 80 dB re 1 μPa corresponds to an rms pressure of 10 mPa (10,000 μPa), whether in air or water. Because of the difference in impedance, for the same rms pressure, the sound intensity in water is much lower than in air.

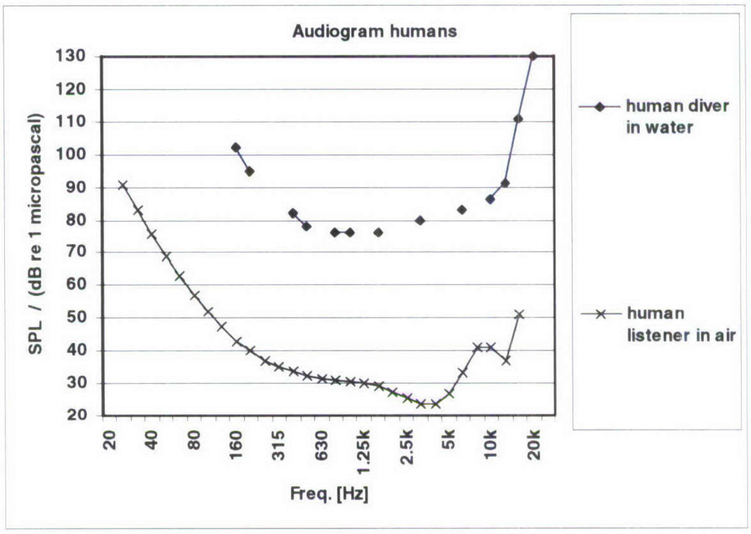

Figure 1 Hearing thresholds from Gerstein.

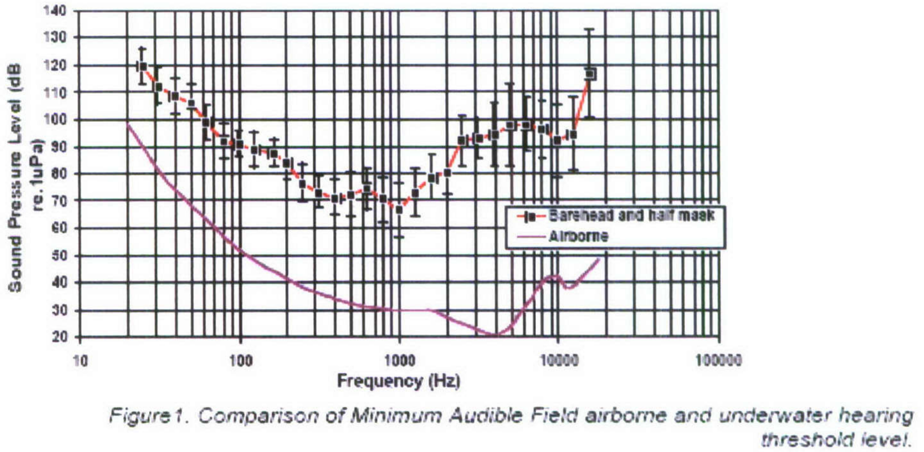

Figure 2 Hearing thresholds from Parvin et al.

[1] A more common reference pressure for use in air is 20 μPa. The numerical value of sound pressure level, expressed in units of 1 μPa, is 26 dB higher than if expressed relative to 20 μPa.

3 Safety thresholds and procedures

Three different documents concerning diver safety thresholds are reviewed in this section. In two of the three documents, the terms 'sound level', 'exposure level' and 'sound pressure level' occur repeatedly and in a manner that implies they are interchangeable. However, these terms actually have quite different meanings. According to the Dictionary of Acoustics [4] *sound pressure level* (SPL) is the mean square pressure expressed in decibels, *sound level* in air is the SPL corrected for the frequency-dependence of human hearing (usually A-weighted) and *sound exposure level* is the integral in time of the squared sound pressure. Because these terms are used interchangeably in the reviewed documents, and because there is no mention in any of them of any frequency-weighting to be applied, it is assumed here that in all cases SPL is intended.

3.1 NATO guidelines

Safety guidelines for human divers are published in a NATO Undersea Research Centre (NURC) publication[5]. The NURC safety thresholds, based on three US references [6, 7, 8] are summarised in Table 1. It is stated that these thresholds should not be exceeded for military divers. It is not specified whether the thresholds apply with or without a protective diving suit or hood.

Table 1 received 'sound level' thresholds for alerted NATO or other military divers from NURC guidelines.

frequency range / kHz	threshold / (dB re 1 μPa)
0.125 – 4	160
4 – 25	167
25 – 31.5	172
31.5 – 250	177

It is unclear from the text, which reads 'The ceiling values may be verified by using an integrating sound level meter with slow detection and 1/3 octave bands', whether it is sufficient to stay below the thresholds in each third-octave sub-band, or whether there is a further requirement for the total SPL in each of the four main frequency bands to be less than the stated threshold (a more stringent requirement). It is assumed that by 'slow detection' is meant 'slow weighting', implying an averaging period of one second.[4]

For recreational divers, a threshold of 154 dB re 1 μPa in the frequency range 600 Hz-2500 Hz is quoted in Section 3.2.3 of the NURC report, referring to further US research. [9].

3.2 DMAC guidelines

The Diving Medical Advisory Committee (DMAC) is an 'independent body, comprising diving medical specialists from across Northern Europe' seeking to 'provide advice about medical and certain safety aspects of commercial diving'[10]. DMAC publishes the following table of sensitivity and tolerance levels [11].

Table 2 received sound pressure level thresholds for commercial divers, from DMAC guidelines. The asterisks (*) indicate values that are 'unlikely to be attained'.

	hooded		non-hooded	
	dB re 20 µPa	dB re 1 µPa	dB re 20 µPa	dB re 1 µPa
threshold of oculo-gyral sensitivity	175	201	165	191
discomfort	180	206	170	196
disorientation	*	*	180	206
intolerance	*	*	192	218

Based on Table 2, the DMAC document specifies recommended maximum sound pressure levels for commercial divers of 201 dB re 1 µPa for non-hooded divers and 211 dB re 1 µPa for hooded ones. This maximum for a non-hooded diver is half-way between the stated thresholds for 'discomfort' and 'disorientation', with 10 dB added for a diver wearing a neoprene hood. It is stated by DMAC that 'the actual thickness of the hood does not greatly alter the degree of attenuation given'. More information about the properties of such a hood can be found in the DMAC leaflet [11].

3.3 Parvin et al guidelines

Joint UK-US research published by Parvin et al. reports the following findings for sound in the frequency range 500-2500 Hz:

- temporary dizziness and related symptoms for bareheaded divers for 'sound levels' above 176 dB re 1 µPa;
- vibration in forearms and thighs at 'sound levels' above 180 dB re 1 µPa;
- sounds tolerated up to the maximum used in the trial 191 dB re 1 µPa;
- advised threshold 'exposure level' for human divers of 155 dB re µPa for use in environmental impact assessment;
- advised threshold 'exposure level', for military divers wearing a diving suit and hood, of 180 dB re µPa.

The maximum SPL permitted by the ethical protocol for Parvin's research was 191 dB re µPa.

3.4 Summary

Published thresholds for military divers (assumed alerted) are summarised in Table 3, followed by thresholds for commercial or recreational divers (assumed unalerted and unprotected) in Table 4.

Table 3 SPL thresholds suggested by NURC and Parvin for alerted military divers.

originator	type of diver protection	frequency range / kHz	maximum value suggested by originator (dB re 1 μPa)
NURC	unspecified	0.125 – 4.0	160
NURC	unspecified	4.0 – 25.0	167
NURC	unspecified	25 – 31.5	172
NURC	unspecified	31.5 – 250	177
Parvin	diving suit and hood	0.5 – 2.5	180

Table 4 SPL thresholds suggested by NURC, DMAC and Parvin for unprotected and unalerted commercial or recreational divers.

originator	frequency range / kHz	maximum value suggested by originator (dB re 1 μPa)
NURC	0.6 – 2.5	154
DMAC	Unspecified [2]	201
Parvin	0.5 – 2.5	155

[2] Thought to be based on research carried out for a tone at 1.5 kHz.

4 Discussion and Recommendations

4.1 Discussion and Recommended Thresholds

The DMAC guidelines for a non-hooded diver exceed the threshold recommended by Parvin et al by 46 dB (see Table 4) – a very large discrepancy. To put the difference into perspective, note that **the DMAC discomfort threshold** for a hooded diver (206 dB re μPa) **is 25 dB higher than the maximum permitted by the ethical protocol for Parvin's research**. The DMAC guidelines appear to be at least partly based on a publication by Montague & Strickland [12]. Using a reference pressure of 0.0002 dyn/cm², this article quotes a figure of 175 dB for 'oculo-gyral effects' and a 'tolerance limit' of 174 dB (quoted in their abstract, and based on their Fig. 6) for non-hooded divers. [3] Converting to modern units these are 201 dB re 1 μPa and 200 dB re 1 μPa. The threshold for oculo-gyral sensitivity is precisely the value quoted by DMAC. The origin of the other values in Table 2 is not known.

By comparison with DMAC, the remaining two sources seem more credible and are reasonably consistent with one another. In particular there is independent support for the threshold of 160 dB re 1 μPa for frequencies up to 4 kHz [13].

The NURC thresholds are assumed to apply to alerted but unprotected divers.
It is understood [3, 14] that the use of a neoprene suit and hood affords significant protection, potentially resulting in higher thresholds for a suited diver, but it is not known by how much; documentation from the UK-US research [14] is required before the thresholds can be safely increased.

The NURC thresholds do not specify whether the protection afforded by a neoprene suit and hood is assumed (see Sections 2.1 and 3.3). A conservative interpretation results in the thresholds recommended in Table 5 below. Thus, until this point can be clarified, sound pressure levels for alerted and hooded navy divers should not exceed the indicated thresholds. The risks for recreational divers may be greater, requiring lower thresholds. The recommended thresholds are intended for use in the context of Navy sonar, although they are also relevant to comparable equipment used in acoustic communications or oceanographic survey applications. They are not suitable for use with short impulsive sounds such as explosions, pile driving or air guns.

[3] The dyne is a CGS unit of force equal to 10 μN, and therefore 0.0002 dyn/cm² = $0.002 \times 10^{-5} / 10^{-4}$ N/m² = 20 μPa. The conversion to a reference pressure of 1 μPa is effected by adding $10\log_{10}(20^2) = 26.0$ dB.

Table 5 Recommended SPL thresholds for alerted and hooded navy divers exposed to sonar transmissions longer than 125 ms. An averaging time of 125 ms is recommended, corresponding to fast sound level weighting. No advice is offered for transmissions shorter than 125 ms.

frequency range / kHz	maximum recommended value (dB re 1 μPa)
0.125 – 4.0	160
4.0 – 25.0	167
25 – 31.5	172
31.5 – 250	177

The risk of injury caused by accidental exposure of divers to high levels of underwater sound **can be reduced by updating the DMAC guidelines** with advice from research more recent than that of Montague & Strickland (1961) [7].

4.2 Other Recommendations

In matters affecting human safety, it is considered imperative to minimise the risk of error resulting from incorrect or ambiguous terminology. The terms 'sound level' and 'exposure level' are defined by Morfey's Dictionary of Acoustics [15] only for airborne sound.

- For underwater sound we propose that 'sound exposure level' be defined as the variable L_E in the following expression in decibels[15].

$$L_E \equiv 10\log_{10}\frac{E}{p_{\mathrm{ref}}^{\ 2} t_{\mathrm{ref}}}$$

where E is the time-integral of instantaneous pressure squared

$$E \equiv \int p_{\mathrm{W}}(t)^2\,\mathrm{d}t\,,$$

and the W subscript indicates that the pressure is to be weighted according to hearing sensitivity. For airborne sound, by default the pressure would be A-weighted. In water, it is not obvious what weighting to use, and sometimes it may be appropriate not to use any weighting. Thus, the weighting used should be stated explicitly.

- It is recommended that the term 'sound level' be avoided for use in water, except in the context of a *specified* animal or group of animals, with corresponding (specified) weighting curves.

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[7] U.S. Department of Labor, OSHA Technical Manual, Section III, Chapter 5.

[8] Naval Submarine Medical laboratory, Report No. 1223, 13 June 2002.

[9] Naval Submarine Medical Research Laboratory,
Report No. 1203, 30 September 1996.

[10] http://www.dmac-diving.org/

[11] *The effect of sonar transmission on commercial diving activities,*
The Diving Medical Advisory Committee, Recommendations DMAC 06 – March 1981, from http://www.dmac-diving.org/guidance/DMAC06.pdf

[12] W.E. Montague & J. F. Strickland,
Sensitivity of the water-immersed ear to high- and low-level tones,
J. Acoust. Soc. Am. 33, 1376-1381 (1961).

[13] see Undersea & Hyperbaric Medicine, 1996, vol 23, supplement, Session D, Exposure to low frequency waterborne sound (39-44).
the following remarks are particularly relevant:

Clark et al. ‘No prolonged adverse vestibular aftereffects were detected in divers exposed to 15 min cumulative (vice continuous) 240-320 Hz U/W sound at 160 dB (re 1μP) after 10-14 exposures.’

Steevens et al. ‘For acute exposures, underwater sound at levels less than 160 dB re μPa appear to be well tolerated for frequencies between 125 and 6000 Hz.’

Schlichting et al. ‘Acute exposures to low frequency sound [order 100 Hz] as intense as 160 dB re 1μPa were well tolerated by subjects’.

Parvin & Nedwell.
‘it is felt that an uninformed diver … may be disturbed by … waterborne sound [for SPL up to160 dB re μPa^2] at frequencies 300 Hz and below’.

Steevens et al. 'At SPLs of 160 dB and higher both auditory and non-auditory effects may prove intolerable to working divers'.

[14] S.J. Parvin & S.L. Searle (1998) Underwater sound perception by divers and the protection from waterborne noise provided by a neoprene hood, DERA/CHS/PP5/TR980078/1.0.

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6 Signature

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15. ABSTRACT (MAXIMUM 200 WORDS (1044 BYTE))

High levels of underwater sound can be harmful to human divers, as they can result in hearing damage or damage to other organs, either directly, or indirectly by causing a panic reaction. Published recommendations for the maximum safe underwater sound level are reviewed. The results of the review are presented in the form of safety thresholds of underwater sound for divers, in the frequency range 125 hertz to 250 kilohertz.

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high frequency	underwater sound
underwater acoustics	hearing thresholds
underwater sound	safety thresholds

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